



The Rock Varnish Revolution: New Insights from Microlaminations and the Contributions of Tanzhuo Liu

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Abstract

Rock varnish is a coating composed of clay minerals cemented to rock surfaces by oxides of manganese and iron. Although this dark brown-to-black accretion is most noticeable in arid regions, it occurs in all terrestrial weathering environments. Scholarly varnish research started with Alexander von Humboldt, when he asked how this external accretion forms and why manganese concentrations in varnish are 10^1 – 10^2 greater than in potential source materials. In the ensuing two centuries, investigations into rock varnish have been characterized by researchers studying only a handful of samples who have often used limited data to draw general conclusions. In contrast, nearly two decades of work by Tanzhuo Liu of Columbia University has yielded more than 10,000 varnish microstratigraphies obtained from rock depressions, analyses of which have provided new insights into the origin of rock varnish and the nature of climatic change in deserts, in addition to opening new research avenues in geomorphology and geoarchaeology.

1 Introduction

Rock varnish is a paper-thin coating that covers rock surfaces in all terrestrial weathering environments, but is most abundant in rocky deserts – hence the common term desert varnish. Two centuries of varnish researchers, initiated by von Humboldt (1812), have focused largely on answering four basic questions. What are its fundamental physical, chemical and biological characteristics? What is its origin? Can varnish be used to understand paleoenvironmental conditions? Can varnish be used as a chronometric tool to help solve geomorphic and archeological problems? A brief review of the status of research on these questions sets the stage for a discussion of recent advances by Tanzhuo Liu that have revolutionized rock varnish research.

Research on the basic characteristics of varnish has addressed the environment of varnish occurrence, thickness, sheen, mineralogy, chemistry, surface, and cross-section textures as viewed by light and electron microscopy, as well as post-depositional modification. A summary of present-day understanding is that ‘desert varnish’ is a misnomer, because the same coating exists in a host of different environments, and that ‘rock varnish’ is a better term (Dorn and Oberlander 1982). Varnish is typically $<20 \mu\text{m}$ thick, but can reach thicknesses $>200 \mu\text{m}$ (Dorn 1998). The most common elements in varnish (Si, Al) derive from the clay minerals that typically make up two-thirds of varnish (Potter and Rossman 1977). Manganese (Mn) and iron (Fe) oxides provide varnish its color; a dark brown-to-black coloration occurs when elemental concentrations of Mn and Fe are about equal and together typically comprise about a fifth of varnish, and but the color turns more and more orange when manganese concentrations drop. The sometimes shiny appearance occurs when the surface has a very smooth texture with high manganese

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concentrations (Dorn and Oberlander 1982). The dominant minerals are clays (Potter and Rossman 1977), the manganese oxide family of birnessite (McKeown and Post 2001; Potter and Rossman 1979), and iron oxides. The use of back-scattered electron microscopy and high-resolution transmission electron microscopy has revealed a multitude of varnish textures largely imposed by the layered nature of clay minerals, but this layering is sometimes broken up by post-depositional leaching and reprecipitation of manganese and iron oxides (Garvie et al. 2008; Krinsley 1998; Krinsley et al. 1990).

One major thread of research on the origin of varnish prior to the use of electron microscopes focused on the underlying rock as the source of varnish constituents. However, electron microscopy revealed that varnish is a coating, applied externally (Dorn and Oberlander 1982; Krinsley et al. 1995; Potter and Rossman 1977). A second major thread of research on varnish genesis deals with explaining the 60-to-100-fold enhancement of manganese in varnish, when compared with abundances in the surrounding environment, as coming from biological agencies such as bacteria (Dorn and Oberlander 1981; Kuhlman et al. 2006) or abiotic processes (Engel and Sharp 1958; Madden and Hochella 2005).

There are four general conceptual models to explain the origin of rock varnish (Figure 1), reviewed in detail elsewhere (see Dorn 2007; for an expansive review of this literature). The first model, a hypothesis that has remained unfalsified, explains the great enrichment of Mn in varnish from abiotic geochemical fractionation of Mn (Figure 1A) (Engel and Sharp 1958; Krauskopf 1957), and its enrichment by an additional abiotic nanoscale process that oxidizes Mn (Madden and Hochella 2005). The second hypothesis, the polygenetic model (Figure 1B), starts with rare oxidation and concentration of Mn (and Fe) by bacteria. Wetting events dissolve nanometer fragments of oxide from bacterial casts, and these are cemented to rock surfaces through interactions with interstratified clay minerals supplied by dust (Dorn 1998; Krinsley 1998; McKeown and Post 2001; Potter 1979). The third explanation (Figure 1C) involves the rich variety of organisms that grow on or near varnish, where these lithobionts themselves (or their organic remains, such as polysaccharides) either concentrate Mn and Fe, and/or bind varnish together. The fourth, and most recent, explanation (Figure 1D) for varnish genesis involves silica binding of loose detrital grains, organics, and aerosols (Perry and Kolb 2003; Perry et al. 2006).

Researchers exploring the potential use of varnish as an indicator of paleoenvironmental change have examined different physical, biological, and chemical characteristics, starting with morphologic changes between botryoidal and lamellate textures that might reflect changes in the abundance of dust (Dorn 1986). Detrital fragments of volcanic ash also provide chronostratigraphic insight (Harrington et al. 1990). The presence of Mn-rich varnish is thought to indicate that the particular location of occurrence was once arid or semi-arid (Biagi and Cremaschi 1988; Dorn and Dickinson 1989; Dragovich 1994; Marchant et al. 1996). Organic remains in varnish such as biominerals, amino acids, ratios of organic carbon with different temporal stabilities, and stable carbon isotopes might yield insights into ancient environments (Dorn and DeNiro 1985; Frink and Dorn 2001; Nagy et al. 1991; Perry et al. 2003, 2007).

Rock varnish has also been used to date when a rock was exposed or used for cultural activities (Dorn 2007; Loendorf 1991; Whitley 2008). The methods proposed include quantifying progressive accumulation of manganese and iron, a darkening appearance over time, changes in the ratio of mobile-to-immobile cations, finding historic materials such as steel in a petroglyph, the abundance of lead and other 20th century anthropogenic pollutants, the ratio of mobile and more stable carbon, the radiocarbon dating of carbonate, organic matter and oxalate within, under or on top of varnish, and microlaminations seen in varnish thin sections.

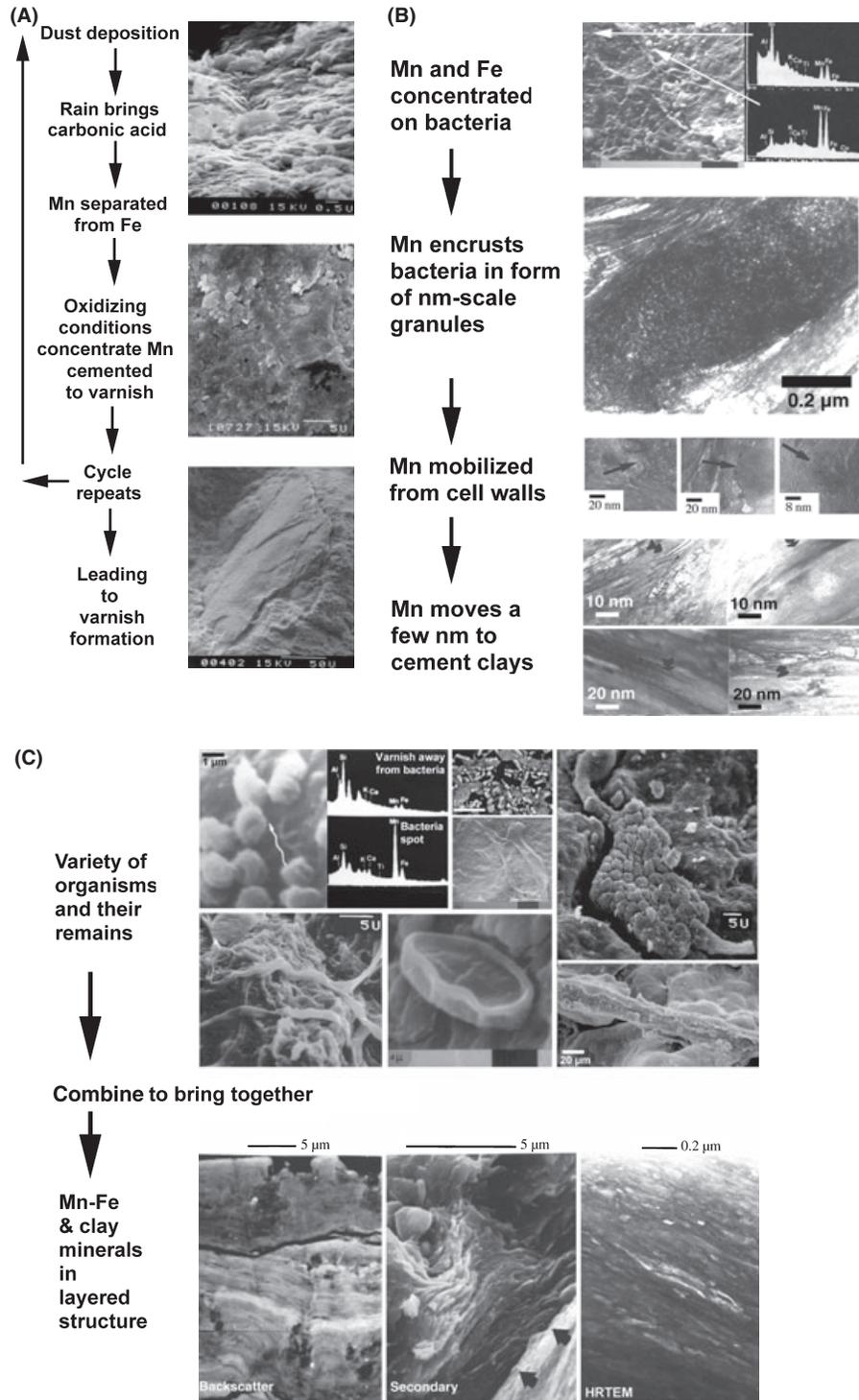


Fig. 1. Conceptual models of rock varnish formation. (A) Abiotic enrichment of Mn. (B) Polygenetic where bacteria enrich Mn that is then cemented by clay minerals. (C) Lithobionts or their remains bind varnish. (D) Silica binding of varnish.

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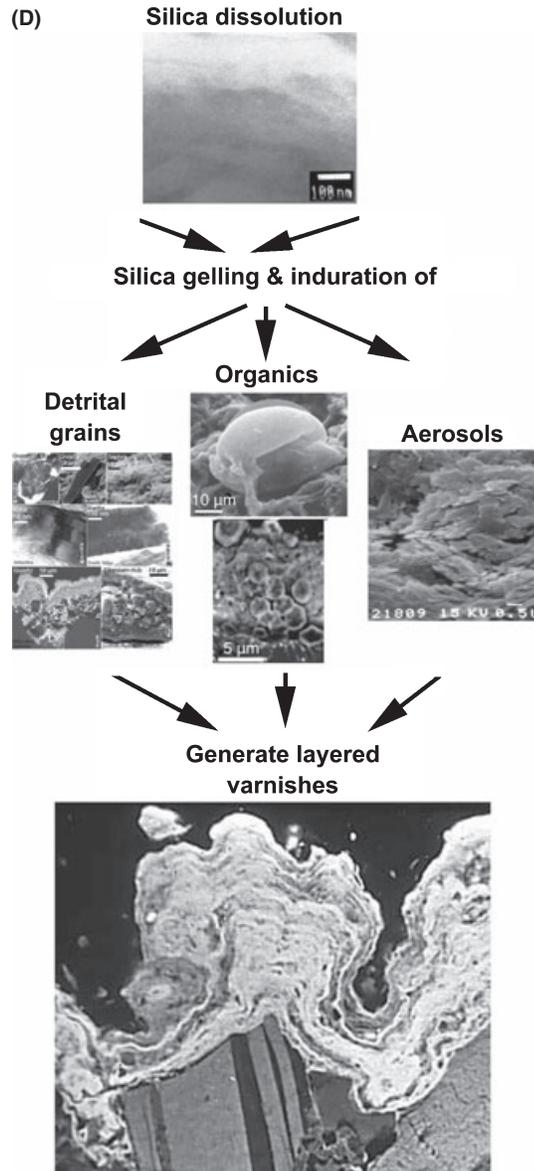


Fig. 1. (Continued)

All of the above paleoenvironmental and chronometric methods are considered by most researchers to be experimental. However, the approach to the study of rock varnish microlaminations (VMLs), developed by Tanzhuo Liu, has arguably moved beyond the experimental stage and is the focus of this study. Tanzhuo Liu has spent the past 17 years compiling and analyzing a data set of unique numerical magnitude and significance. During this time, he has analyzed more than 10^4 microsedimentary depositional sequences of rock varnish or VML patterns (Figure 2), and his doctoral dissertation alone included an analysis of >4000 microstratigraphies (Liu 1994).

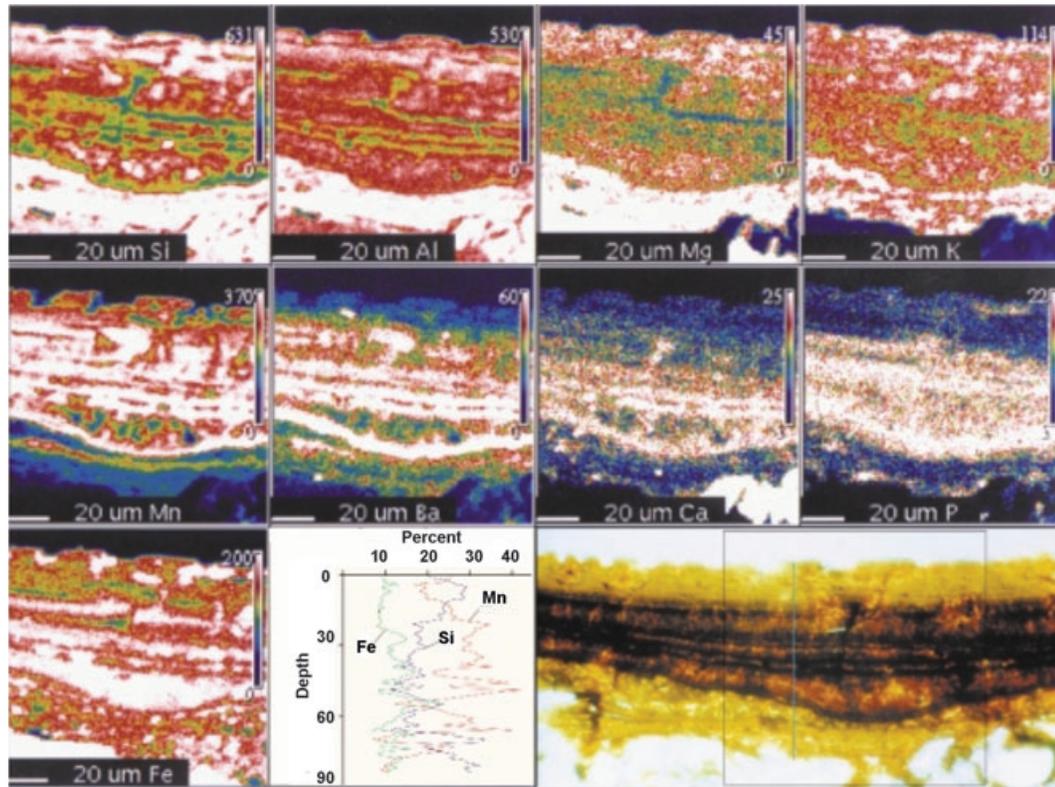


Fig. 2. The varnish microlamination pattern is seen in an ultra-thin section in the color frame in the lower right. Yellowish layers indicate extreme aridity; orange layers indicate drier climatic intervals, and black layers indicate wetness. Within this section, the square central section shows the location where the abundance of different elements can be seen through the various X-ray maps in this figure. The line in the color frame indicates the location of an electron microprobe transect showing concentrations of Mn, Si, and Fe. The patterns seen in these measurements reflect many prior observations in the normal science literature: (i) that the yellow and orange layers have the least Mn and the most Si, Al, Mg, and K contributed by clays; and (ii) that although Fe abundance remains fairly steady in the orange and black layers, Mn abundance correlates with the darkness of the black layers. Image courtesy of T. Liu.

2 Tanzhuo Liu's Approach

Varnish microlamination sections are much thinner than regular geological cross-sections used in petrology in order for light to transmit through varnish layers. The use of traditional geological thin-sectioning techniques often results in the partial or complete abrasion of varnish. To address this problem, Tanzhuo Liu made ultrathin sections from a rock chip coated with varnish, encased in epoxy, and oriented so that the varnish is perpendicular to the section face. The rock chip is abraded with progressively smaller grit sizes to make a cross-section, before being flipped over, re-encased with epoxy, and polished from the other direction. The last stages of polishing involve using a fine (submicron) aluminum paste that prevents the complete abrasion of the section. Careful orientation of the rock chip in the epoxy and polishing bring out the VML patterns, and by examining the first cross-sectional face in reflected light, it is possible to avoid those textures that are characteristics of post-depositional modification. The technique results in transmitted light microscope images that highlight black, yellow, and orange layers.

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The core of Tanzhuo Liu's research rests in calibrating the VML patterns. Thus, samples must be collected from stable rock varnish, varnishes that have accreted in a subaerial environment, and been exposed only to deposition of dust and precipitation and dew, and on landforms with independent age control. All other types of rock varnish (Dorn 1998), including varnishes on rock surfaces that are too close to the soil surface, microsites susceptible to water flow or the collection of water, and varnishes that initiated in a rock fracture that was later exposed by spalling, are ignored. This last type of varnish is actually the most commonly collected variant, because many researchers explicitly try to collect the 'best looking' or 'darkest' varnish, and these typically start inside rock fractures (Cervený et al. 2006; Dorn 1998).

By analyzing VML sequences in Death Valley, California, Liu (1994) identified 'layering units' (LUs) with replicable characteristics (Figure 3). Liu (1994) was able to correlate yellow layers to the Holocene (LU-1) and the Eemian (LU-5) interglacial (Figure 3) by

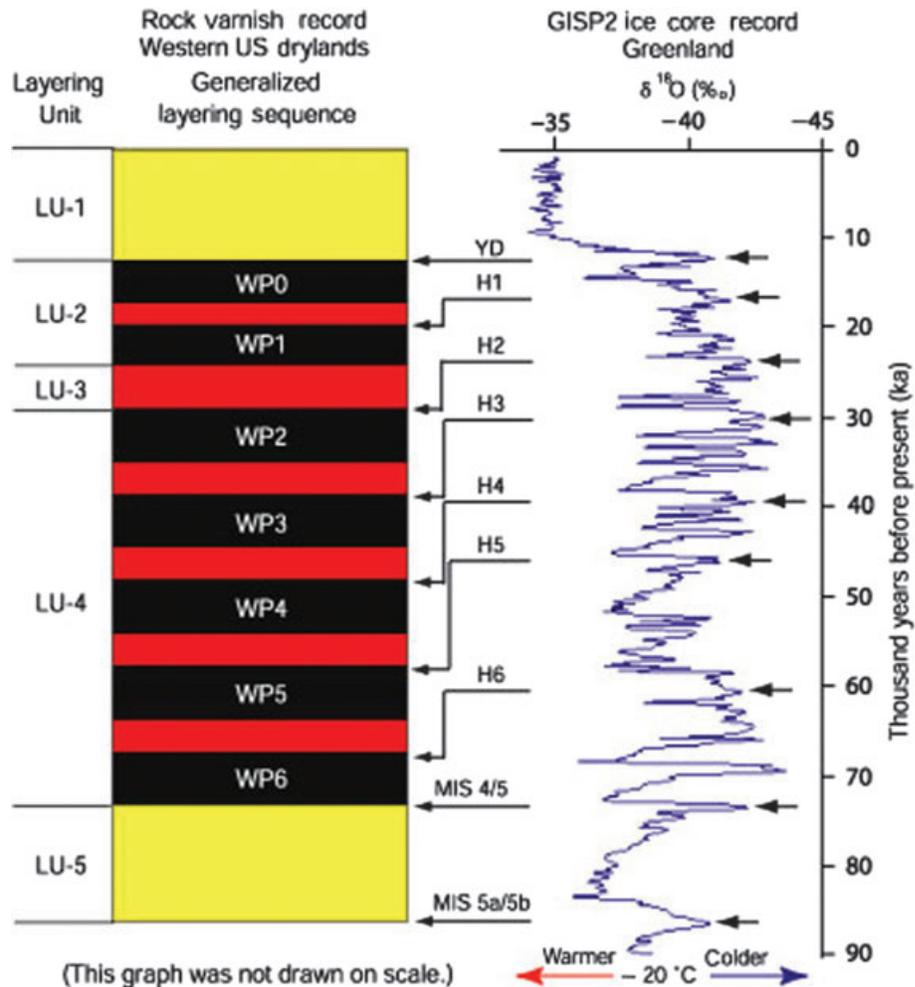


Fig. 3. Initial findings revealed a replicable pattern of late Pleistocene layering units (LU-1 through LU-2) and later that the pattern of black layers (WP for wet periods) have a possible correlation with Northern Hemisphere climate changes recorded in the Greenland ice-core records and Heinrich events (YD, Younger Dryas; H, Heinrich event). Image courtesy of T. Liu.

analyzing samples collected from sites of known age. In between, three LUs (closely spaced, parallel double black lines) form LU-2; a thick orange band forms LU-3; and a series of five black bands form LU-4 (Figure 3). The black bands were equated with wet periods (WP) that correlate with global climatic changes (such as the Younger Dryas and Heinrich Events) documented in the Greenland ice-core record (Liu and Broecker 2008b) (Figure 3).

Sections compiled from sites of known age provide an introduction to interpreting VML sequences. Figure 4 exemplifies the types of microsedimentary sequences that were analyzed to develop a chronometric picture of the late Pleistocene in the Great Basin of the USA (Liu 2003; Liu and Broecker 2008b; Marston 2003). Compare the lowest (oldest) VML in each section in Figure 4 with the generalized pattern revealed in Figure 3. Examining Figure 4H, we see that the lowest VML is WP2, an event that occurred about 24,000 years ago in Figure 3. Above WP2, the section displays the double black layers of LU-2 (WP0 and WP1) and above that lies the LU-1 layer.

Two general types of complication arise in interpreting sections in Figure 4. First, small changes in section thickness change its optical appearance and cause apparent thinning

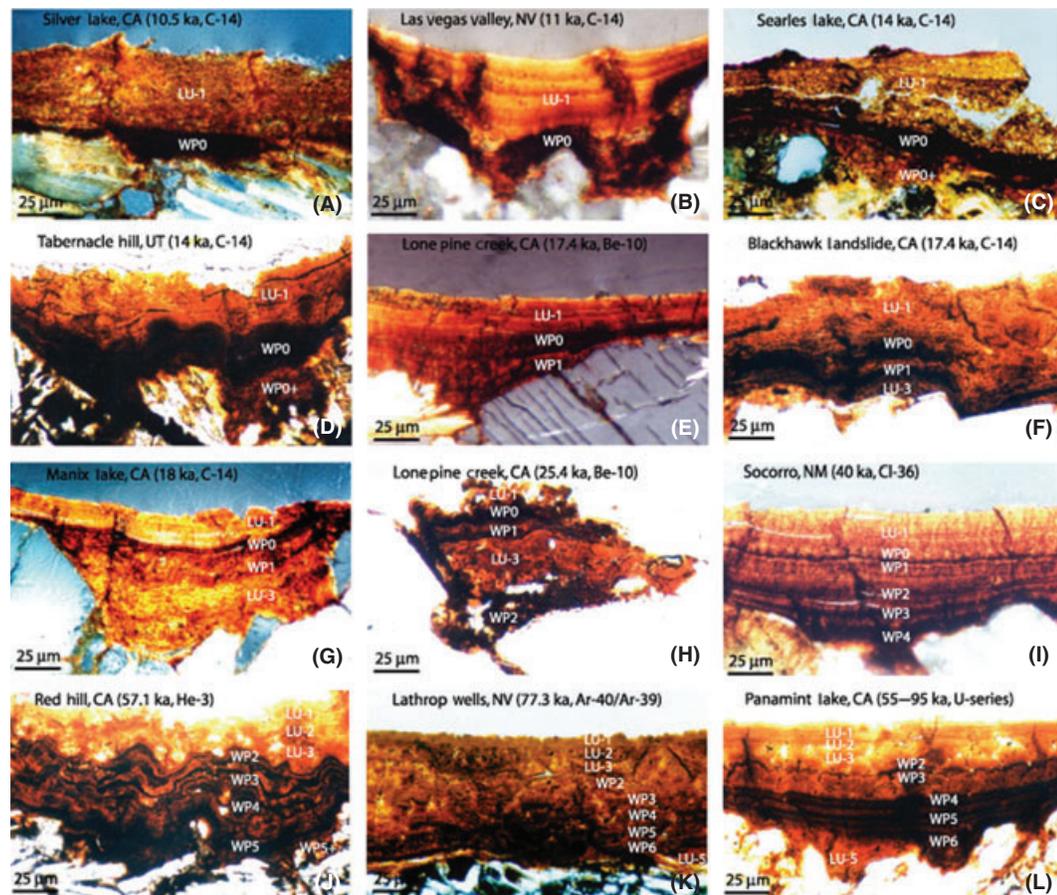


Fig. 4. Varnish microlamination pattern in late Pleistocene varnish samples collected from geomorphic features in the western USA dated through many different types of radiometric methods including radiocarbon, uranium-series, and cosmogenic nuclides. Ages for the earliest that varnishing could have started are indicated in thousands of calendar years (ka). The layering units are generalized in Figure 3. Image courtesy of T. Liu.

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and thickening of the VMLs. Second, even if varnish sections dominated by post-depositional modification are explicitly avoided, disequilibria among the cementing agents of varnish (Mn and Fe) can result in a post-depositional modification that often interrupts the layering pattern (evidence of this is provided by vertical cross-cutting veins filled with Mn, seen best in Figure 4A,G,I).

Nevertheless, despite interruptions in the layering pattern, reproducible microsedimentary sequences emerge and replication in patterning can be identified in the same deposit on the same alluvial fan (e.g. Figure 5A), on morphologically correlated deposits on

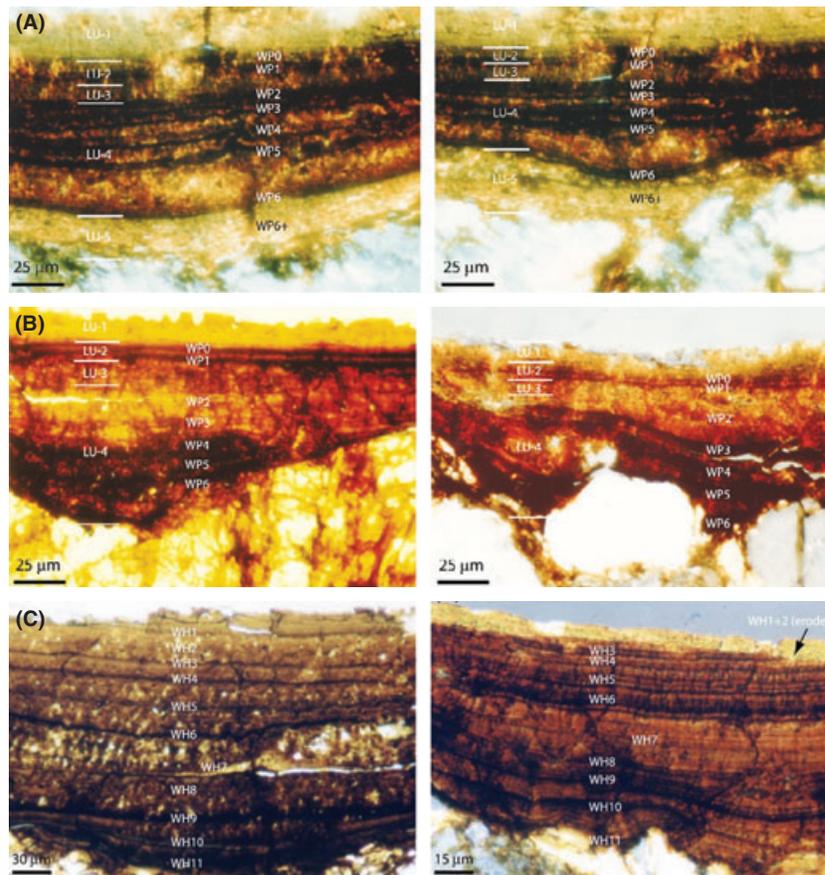


Fig. 5. Replication of varnish microlamination (VML) patterns occurs throughout Liu's research across different distances. (A) Late Pleistocene record in two microbasins from the same alluvial fan deposit in Death Valley, California, which started to form at the end of the last major interglacial before 74 ka (LU-5). The record of varnish deposition is continuous. Note zones of disequilibria disturbing VML in cross-cutting Mn stringers and in oval zones of cation leaching that wash out black wet periods (WP) bands. Despite these interruptions, the replication is obvious (Liu 1994). (B) Late Pleistocene record in two microbasins from the same morphologic unit on Galena Canyon fan (left image) and Warm Springs Canyon fan (right image), Death Valley, California (Liu and Broecker 2008b). (C). Holocene record of two microbasins from a terminal Pleistocene-dated shoreline in the adjacent closed basins of Searles Valley (left image, sequence starting ~16.8 ka) and Panamint Valley (right image, sequence starting ~18.4 ka), eastern California (Liu and Broecker 2007). Some problems that can occur in thin section preparation can be seen in eroded varnish at the very top of the Searles Valley (left) image. The potential of VML and complications in interpretation can be seen in uniformity near the top of the Panamint Valley (right) image identified by the arrow. The WH abbreviation signifies a 'Wet Holocene' period, in contrast with the WP annotations of wetter phases in the late Pleistocene. Image courtesy of T. Liu.

adjacent alluvial fans (e.g. Figure 5B), and on similarly aged shorelines in adjacent closed basins in the western USA (e.g. Figure 5C).

Moreover, in some locations, the microlaminations may be of high-enough resolution to relate to the changes in climate that occurred at the end of the Pleistocene, although greater abundance of moisture enhances rates of varnish accretion and also promotes the growth of the microcolonial fungi and lichens that dissolve Mn and Fe and destroy VML patterns. Figures 5C and 6 illustrate higher-resolution VML patterns produced where varnishing rates are rapid, but where varnish-dissolving organisms have not yet colonized.

A vast majority of varnishes do not last for long periods of time (<300,000 year). However, varnishes that accumulate at extremely slow rates (of less than a micrometer per ka) in very shallow (<1 mm deep) microbasins in the most xeric positions on the tops of weathering-resistant boulders can preserve a lengthy record for the late Quaternary in the western USA (Figure 7).

It remains, however, that VML has yet to be extensively applied outside the core area of the western USA (there are 10^4 microsedimentary basins in Tanzhuo Liu's library from the western USA, and 2 orders of magnitude fewer basins for the rest of the world; <http://www.vmldatinglab.com>). Moreover, although VML sequences have been recognized in western China (Zhou et al. 2000), the Indus region of India, Negev Desert in Israel, and Argentina (Liu 2008), and some research in the Sahara (Zerboni 2008) and Australia (Lee and Bland 2003) is consistent with the basic premise of VML, it will require a concerted effort to move global VML research from the experimental to the practical stage.

3 Implications for Rock Varnish Research

Varnish microlaminations provide the first clear indication that rates of varnish accretion in deserts are of the order of $10^0 \mu\text{m}/\text{ka}$ (Dorn 1998; Liu and Broecker 2000), although they vary considerably (e.g. Figures 4–6). Growth rates of less than a 10^0 per ka occur in particularly xeric microbasins and during drier paleoclimatic intervals, and rates can reach 10^1 per ka in mesic microbasins and during wetter time periods (in what are now xeric environments). Varnish accretion can also occur at rates $>10^2$ per ka in places, like slag piles, that are inimical to lichen growth (Dorn and Meek 1995), although such fast growth rates are quite rare. Regardless, the implication for studies of varnish genesis is that whatever makes varnish must involve at least one rate-limiting step, and any viable hypothesis for the origin of varnish (Figure 1) must explain this mechanism.

The notion that abiotic pH/Eh fluctuations can release enough Mn to make varnish has remained unchanged for 50 years (Figure 1A; Engel and Sharp 1958), starting with rainfall that leaches Mn from dust occurs on a regular basis. Consequently, abiotic explanations for the geochemical enhancement of Mn, and its subsequent cementation to the rock surface with clays and iron, cannot currently explain very slow growth rates. For example, if a dust layer of particles $100 \mu\text{m}$ thick resting in a microsedimentary basin 2 mm wide leaves behind its manganese (at a typical concentration of 0.02%) in a single wetting event per year, and that same Mn cements clays to the rock surface at a ratio of one part manganese to ten parts clay, depending on different geochemical assumptions, the resulting layer of varnish would be on the order of 10^{-1} – $10^1 \mu\text{m}$ thick if a single-wetting event occurred every year. Resupplying the dust between wetting events, multiplying by, say three wetting events a year, and then by a thousand years gives a minimum varnishing rate on the order of $10^3 \mu\text{m}/\text{ka}$. Moreover, there is no reason why abiotic processes would have a severe rate-limiting step.

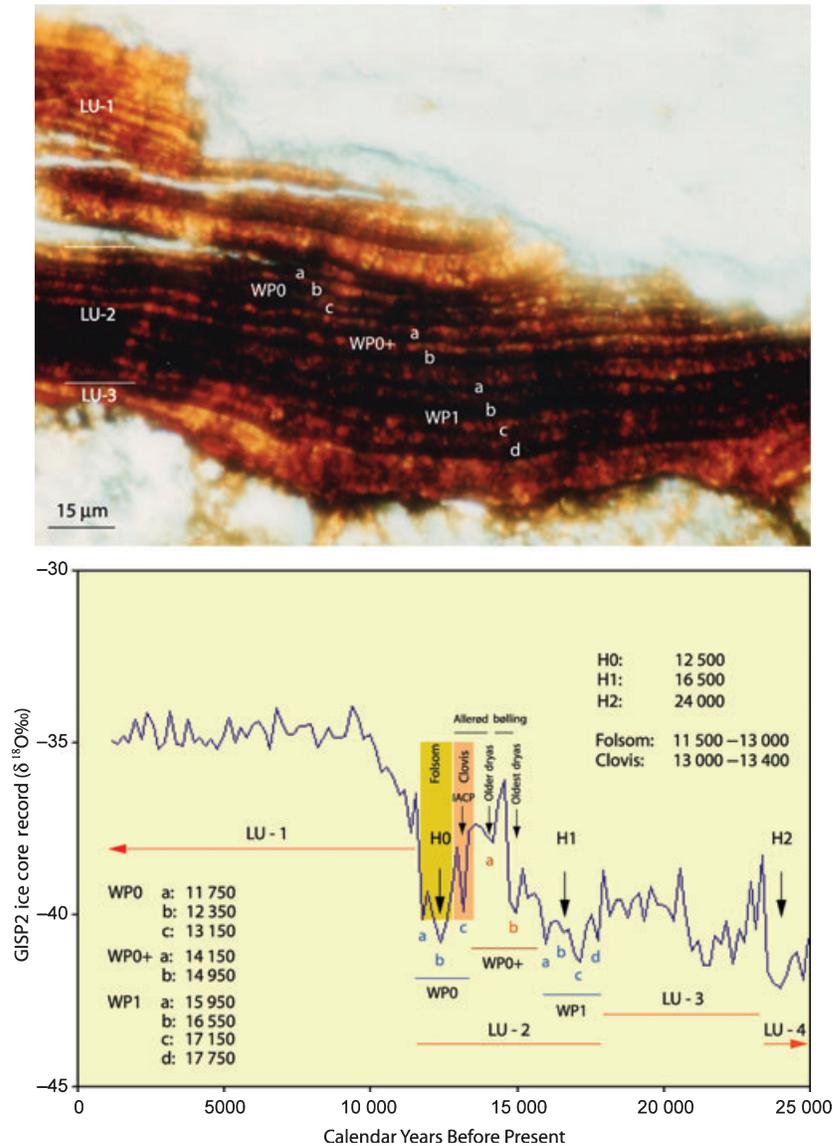


Fig. 6. A varnish ultra-thin section from Galena Canyon fan in Death Valley (with the upper layers irregularly polished off during thin section production) forms the visual backdrop for the age correlation of the different terminal Pleistocene varnish microlamination (VML) patterns. The age correlation presented here derives from independent numerical age control from geomorphic surfaces that host varnish sections and from the Greenland ice-core record as a correlation. For the sake of illustration and temporal recognition, the well-known Folsom and Clovis lithic technologies are placed in this high-resolution VML sequence. The nomenclature of layering units (LU), Heinrich Events (e.g. H0, H1, H2), wet periods in the late Pleistocene (WP) identified by black varnish layers follows previous illustrations. What is new here are higher-resolution wet periods identified by lower case letters (e.g. WPOa, WPOb, WPOc). Image courtesy of T. Liu.

The same basic challenge faces the silica-binding model (Figure 1D). The best insight on rates of silica accretion comes from rates of silica glaze formation (Perry and Kolb 2003; Perry et al. 2006). Observations made on lava flows of known age in the rain shadow of Hualalai and Mauna Loa suggest that silica glaze forms at rates $>10^2 \mu\text{m}/\text{ka}$

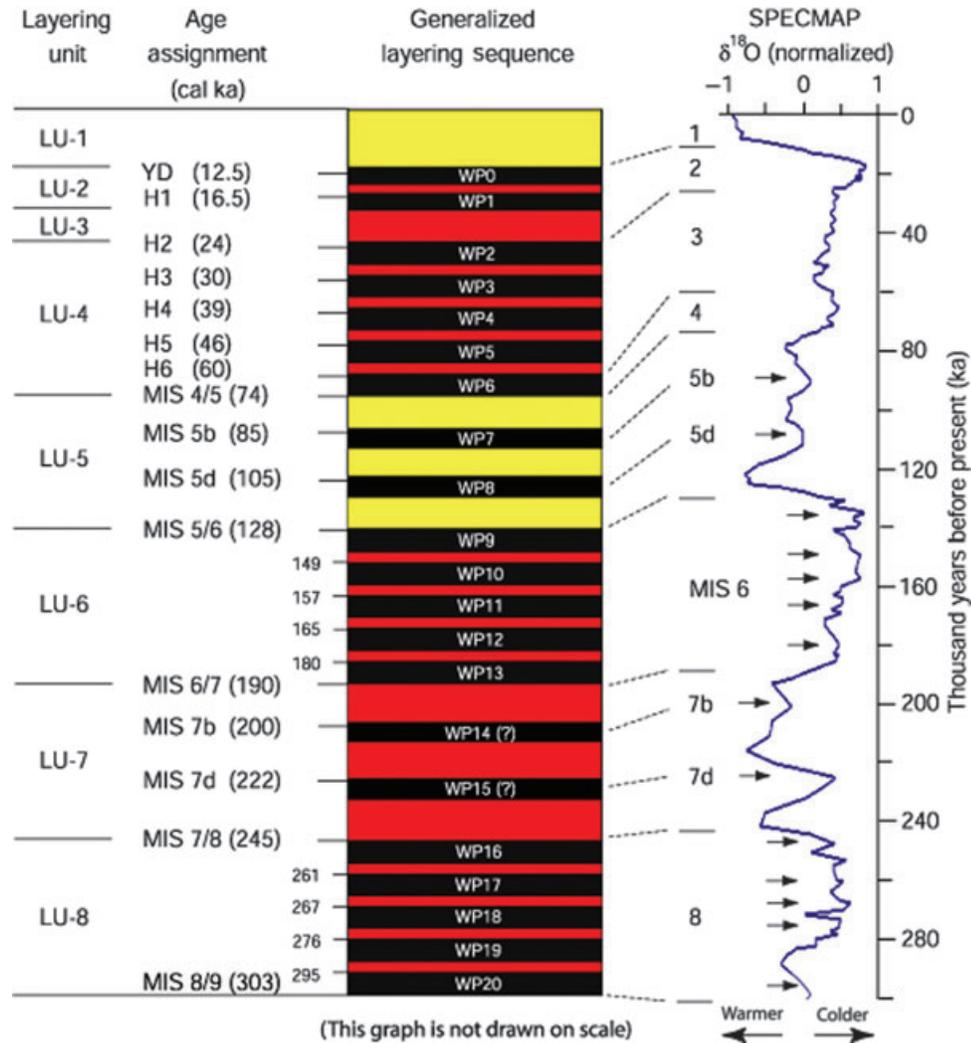


Fig. 7. A generalized late Quaternary varnish microstratigraphy and its tentative correlation with the SPECMAP oxygen isotope record (MIS, marine oxygen isotope stage). Altogether, 21 specific wetter intervals have been found in the western USA varnishes in the last 300 ka (Liu 2003; Liu and Broecker 2007, 2008a,b). The calibration for wet periods (WP) through WP6 are based on numerical ages for geomorphic surfaces. Age assignments for WP7–WP20 are more speculative, because they are based on the tentative correlation of the varnish record with the SPECMAP record (Liu and Broecker 2008b). Image courtesy of T. Liu.

(Curtiss et al. 1985; Dorn 1998; Farr and Adams 1984; Gordon and Dorn 2005), and the literature relevant to silica binding suggests that there should be no severe limiting step that would slow rates of varnishing to those levels observed in VML studies.

Models that suggest organisms enhancing manganese (Figure 1B,C) run into the same difficulty. Consider the notion that a few bacteria oxidize Mn, die, and then the Mn in the cell and forming a sheath around the cell contributes to the varnish. Both sides of an oxide-encrusted bacterial sheath amount to a thickness of about 0.3 μm , and clay minerals compose about 70% of varnish (Dorn 1998; Krinsley et al. 1995; Potter and Rossman 1977, 1979). Consequently, it would take very little bacterial enhancement of Mn to

generate observed varnish growth rates, on the order of a single bacterium each thousand years.

In light of VML research on rates of varnish accretion, also consider recent DNA analyses (Benzerara et al. 2006; Eppard et al. 1996; Kuhlman et al. 2005, 2006; Perry et al. 2006; Spilde et al. 2005). DNA degrades rapidly from the high temperatures found on desert rocks, and the bulk samples analyzed may have ages 'possibly less than 200 years old' (Perry et al. 2003, 436). Thus, given extremely slow rates of varnishing, it does not seem likely that every observed Mn-oxidizing organism is involved in varnish genesis.

Nevertheless, it has been shown that lithobiont forms (e.g. bacteria, fungi) enhance Mn, and using a scanning electron microscope and energy-dispersive X-ray unit, it is possible to determine where Mn or Fe enhancement is spatially associated with the lithobiont form (Dorn 1980, 2007; Dorn and Oberlander 1981, 1982). The morphology of the Mn-enhancing lithobiont forms is consistent with budding bacteria (Hirsch 1974; Perfil'ev et al. 1965), and these forms occur infrequently enough to be consistent with VML research on rates of varnish accretion. Thus, budding bacteria forms are known to exist and concentrate Mn with an occurrence consistent with extremely slow rates of varnishing observed in VML studies.

In summary, prior research on varnish genesis did not consider the existence of one or more severe rate-limiting steps. For those models involving the role of biotic processes (Figure 1B,C), the challenge is that a vast majority of collected varnish samples should *not* be recording processes of varnish formation. For those models relying on abiotic processes (Figures 1A,D), the challenge is to identify if one or more rate-limiting steps exist.

Previous researchers speculated that variations in Mn-concentration might be an indicator of climatic changes (Cremaschi 1996; Dorn 1990; Drake et al. 1993; Jones 1991; Perry and Adams 1978). The general hypothesis is that Mn-rich black microlaminations derive from less-alkaline conditions more favorable for the growth of the Mn-enhancing bacteria. Drier periods generate VMLs with a higher percentage of clays and lower abundance of Mn (Dorn 2007; Krinsley 1998). However, there was little attempt to relate varnish layers to past climate events until Tanzhuo Liu's research on VML opened up a new field of paleoenvironmental research – the study of environmental change at the millimeter-scale on desert rock surfaces. Each VML microbasin sequence provides spatially specific, millennial-scale data on the sequence of wetter or drier conditions experienced by a single rock-surface depression. At first glance, this topic might seem trivial. However, if a future Martian rover were to identify a VML sequence on a boulder, it could help reveal the sequence of environmental fluctuations that were responsible for forming that component of the Martian landscape (Hausrath et al. 2008; McSween et al. 2009).

In that sense, Liu's VML research is akin to the initial study of a packrat midden (Wells and Jorgensen 1964), a varved core (De Geer 1930), or an ocean core containing ice-rafted debris (Heinrich 1988), all of which can generate insights into a local and much broader-scale phenomenon. In the case of VML, studies based on single-desert landforms can be integrated across an alluvial fan, landslide, talus cone, or glacial moraine. With its focus on the paleoclimatic implications as well as the dating of landforms, VML offers geomorphologists a refined ability to link climate change to landform development.

Consider the topic of avulsions in desert washes (Field 2001), a key issue in suburban expansion in the desert south-west (Committee on Alluvial Fan Flooding 1996). Using Liu's Holocene calibration (Liu and Broecker 2007), a study of fan avulsion events in the Phoenix metropolitan area (Figure 8) reveals that floods have been redirected down different paths throughout the Holocene. There is a slight tendency for the basal VML

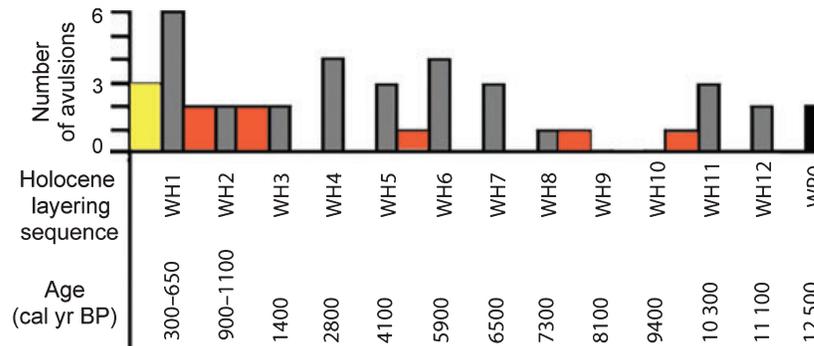


Fig. 8. Histogram of the varnish microlamination (VML) patterns collected from locales where a desert wash channel had been abandoned by an avulsion to another channel. Each avulsion tabulated here records when varnish started to grow in the abandoned channel, where all study sites are in the Phoenix metropolitan region. The histogram was compiled through the analysis of VML microbasins at 42 avulsion locales, providing a preliminary insight into the connection between climatic changes and avulsions.

layer to be laid down in a WH – perhaps suggesting that avulsions are more common during the wetter intervals of the Holocene.

Alluvial-fan researchers have long speculated on the connections of these features to climate change (Dorn 2009). However, no sedimentological property in an alluvial fan reveals whether a deposit is associated with a specific climatic regime, because all different types of deposits occur in all different types of climates (Blair and McPherson 1994). In contrast, VML permits the direct correlation of alluvial-fan deposits and climatic change (Liu and Broecker 2008b). For example, VML analyses of a debris-flow fan in Death Valley (Figure 9) led to the conclusion: ‘that emplacement of these deposits was more likely to have occurred during relatively wet periods of the Holocene’ (Liu and Broecker 2008b, 518). Although this conclusion does not support the most popular model connecting fan aggradation to climatic change (Bull 1991), nor falsify the existing western USA paradigm that interprets alluvial fans as being the product of a transition from wet to dry climates (Bull 1991, 1996; Reheis et al. 1996), it does suggest that it may be necessary to reevaluate our assumptions about how climatic changes influence individual desert landforms.

Varnish microlamination also has the potential for dating desert landforms and related (in this case tectonic Figure 10) events, by providing chronometric insight into the exposure of a rock surface, such as boulders on an alluvial-fan, through events that reset the VML clock.

Moving beyond specific landforms, VML research reveals insight into the broad nature of climatic changes that have taken place within the Mojave Desert in eastern California. Again the insights obtained from VML sequences, into the fluctuations between wet and dry conditions, provide a different perspective to that gained from other proxy records, such as packrat middens, soils, lake cores, or aeolian deposits (Bell et al. 1998; Fleisher et al. 1999; Liu and Broecker 2008a,b; Liu and Dorn 1996; Liu et al. 2000; Moore et al. 2001). Liu’s research also suggests that VMLs correlate with global signals (Figures 3 and 7), such as Heinrich Events, the Younger Dryas, and millennial-scale climatic changes recorded in the Greenland Ice Core (Liu and Broecker 2008a,b).

Varnish microlamination research also offers geoarchaeologists the ability to correlate events, at the time scale of millennia, and in the western USA, for example, it is now possible to assign ages to such features as geoglyphs (Cervený et al. 2006), petroglyphs (Cremaschi 1996; Martin et al. 2008; Zerboni 2008), and artifacts (Liu 2008). In so

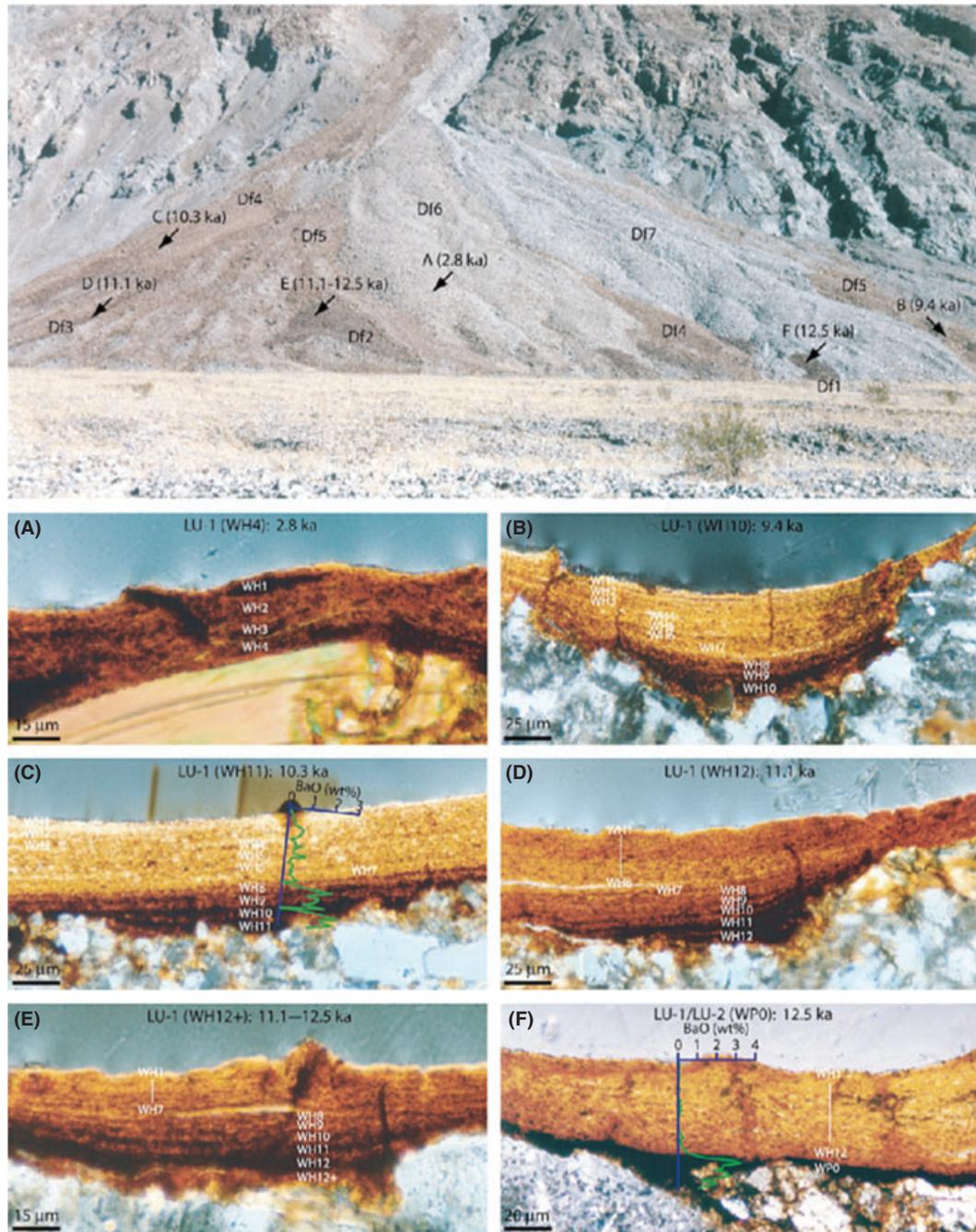


Fig. 9. Varnish microlamination (VML) sequences on different alluvial-fan surfaces on an unnamed, but commonly photographed, debris-flow fan on the east side of Death Valley, California. The letters on the ground photograph match the VML sequences. Image courtesy of T. Liu.

doing, VML also gives archeologists the opportunity to ‘understand interactions between prehistoric humans and their environment’ (Diaz et al. 2002, 58), and potentially provides the opportunity to link prehistoric human behavior to climatic change.

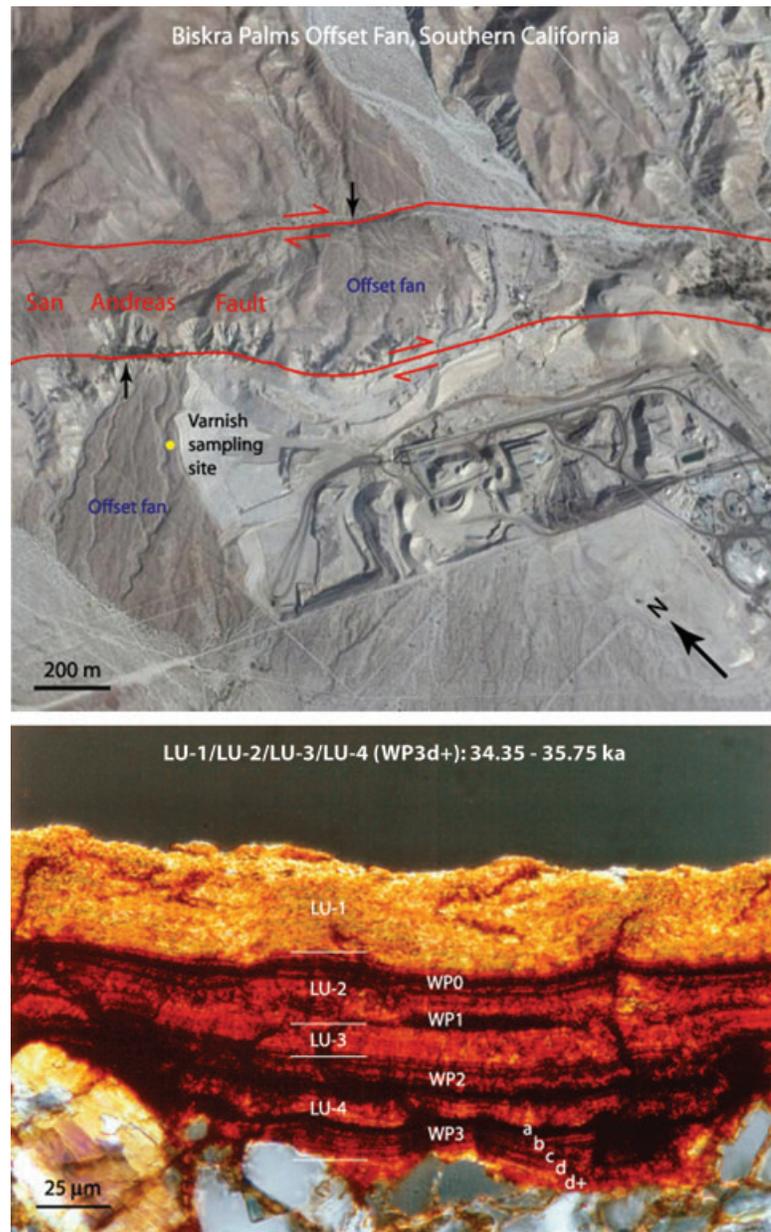


Fig. 10. A tectonically offset alluvial fan along the San Andreas Fault near Indio Hills, southern California, shows the context of a varnish microlamination (VML) age estimate for when the lower fan was faulted away from the source of the fan material. The most certain age for this unit is slightly older than the WP3 until of 30 ka. However, through selection of the most rapidly forming varnish, Liu was able to discern millennial-scale wet periods within the WP3 unit. Using tentative correlations with the Greenland ice-core record, Liu could then assign a tentative more precise age of between 34 and 36 ka. This particular example also illustrates Liu's efforts to continually test the calibration, in this case using a cosmogenic ^{10}Be age of 35.5 ± 2.5 ka for the same offset fan. Because cosmogenic nuclides on alluvial fans suffer from the problem of 'inherited' exposure higher in the drainage, this VML analysis lends confidence to the slip-rate estimate of about 16 mm/year for this segment of the San Andreas Fault. Images courtesy of Tanzhuo Liu.

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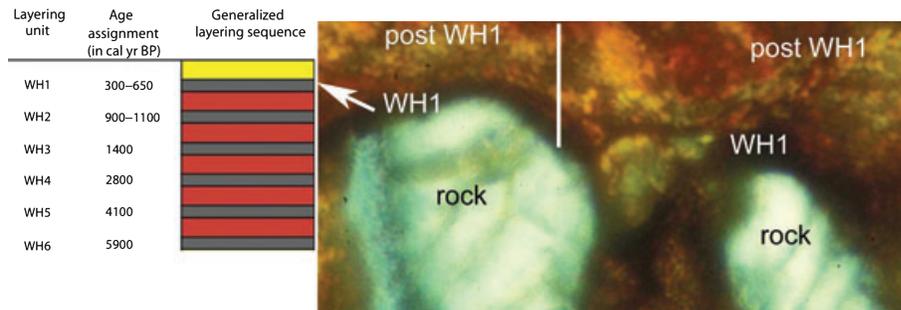


Fig. 11. This ultra-thin section view shows a very thin layer of dark, Mn-rich varnish resting on sandstone grains (rock). This WH1 layer formed during the Little Ice Age, according to Liu's Holocene calibration. The white line indicates the location of electron microprobe measurements.

Varnish microlaminations can also be used to help decipher whether inscriptions are graffiti or have historic significance. An example is an inscription carved into rock in the Glen Canyon National Recreation Area (Figure 11), where the Dominguez-Escalante expedition made a successful crossing of the Colorado River at a location known as 'The Crossing of the Fathers' (now Padre Bay in Lake Powell). Here there is an inscription reading 'Paso Por Aqui Año1776'. Ultrathin sections of relatively fast-growing varnish reveal that the engraving was made during the Little Ice Age (WH1), and that it is not modern (20th century) graffiti and thus warrants conservation.

4 *The past, present, and future*

According to Brown (1996, 16) '[scientific r]evolutions involve challenges to established guiding assumptions. As a result, the set of alternatives that can be seriously considered expands as previously accepted criteria for limiting the range of acceptable alternatives are challenged'. Here I raise the possibility that Tanzhuo Liu's research constitutes a scientific revolution. In the previous sections, I explained how VML has impacted four core arenas of varnish research and helped answer questions about its origin and the implication it has for paleoclimatic interpretation, and dating landforms and geoarchaeological remains. But it is also necessary to compare the nature of research in a field of study prior to the substantive advance. A typical rock varnish study (which I characterize as 'normal science') makes reference to analyses of relatively few samples (Bao et al. 2001; Dorn and DeNiro 1985; Dorn and Oberlander 1981; Dorn et al. 1992; Dragovich 1998; Flood et al. 2003; Garvie et al. 2008; Gorbushina et al. 2002; Harry 1995; Hodge et al. 2005; Krinsley 1998; Kuhlman et al. 2006; Martin et al. 2008; Perry et al. 2006; Reneau 1993; Wayne et al. 2006). Such studies stand in dramatic contrast to Tanzhuo Liu's pioneering approach, which is founded on replicated patterns observed in different desert regions. Thus, it is my contention that he has moved rock varnish research from a field that revolved around individual studies into the arena of comparative endeavor where research results are predicated on rigorous and careful study. If this is the case, it may be useful to make some predictions about what will occur next. It is possible that much rock varnish research will continue to be 'normal science', or that Tanzhuo Liu's (VML) approach will be slow to be adopted by other workers, who will want to test it against their individual experience and methodologies. But it is equally possible that the potential of VML will be enhanced by research conducted by a new generation of geomorphologists and

geoarchaeologists in countries outside the USA where painstaking analytical detail continues to be held in high regard.

Short Biography

Ron Dorn's research focuses on rock coatings, their geography, and application to geomorphology and rock art. He has authored the only book on rock coatings, and he has authored or co-authored papers in these areas for *American Antiquity*, *American Indian Rock Art*, *Annals of the Association of American Geographers*, *Antiquity*, *Cambridge Archaeological Journal*, *Geoarchaeology*, *Geological Society of America Bulletin*, *Geology*, *Geomorphology*, *Heritage Management*, *Journal of Geology*, *Nature*, *Physical Geography*, *Science*, and other journals. Current research involves both theoretical research on the processes of rock-coating formation and empirical research on applying rock coatings to the understanding of geomorphic and archaeological questions. This research with collaborators has been recognized by awards and fellowships from the American Rock Art Research Association, the Arizona-Nevada Academy of Science, the British Geomorphological Research Group, the Geomorphology Specialty Group of the Association of American Geographers, the Geological Society of America, and the US National Science Foundation. Before coming to the Arizona State University in 1988 where he presently teaches, Dorn taught at the Texas Tech University. He holds an AB and MA in Geography from Cal Berkeley and a PhD in Geography from UCLA.

Note

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